Explore Information Content of CLARREO Hyperspectral Data

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Presentation outline

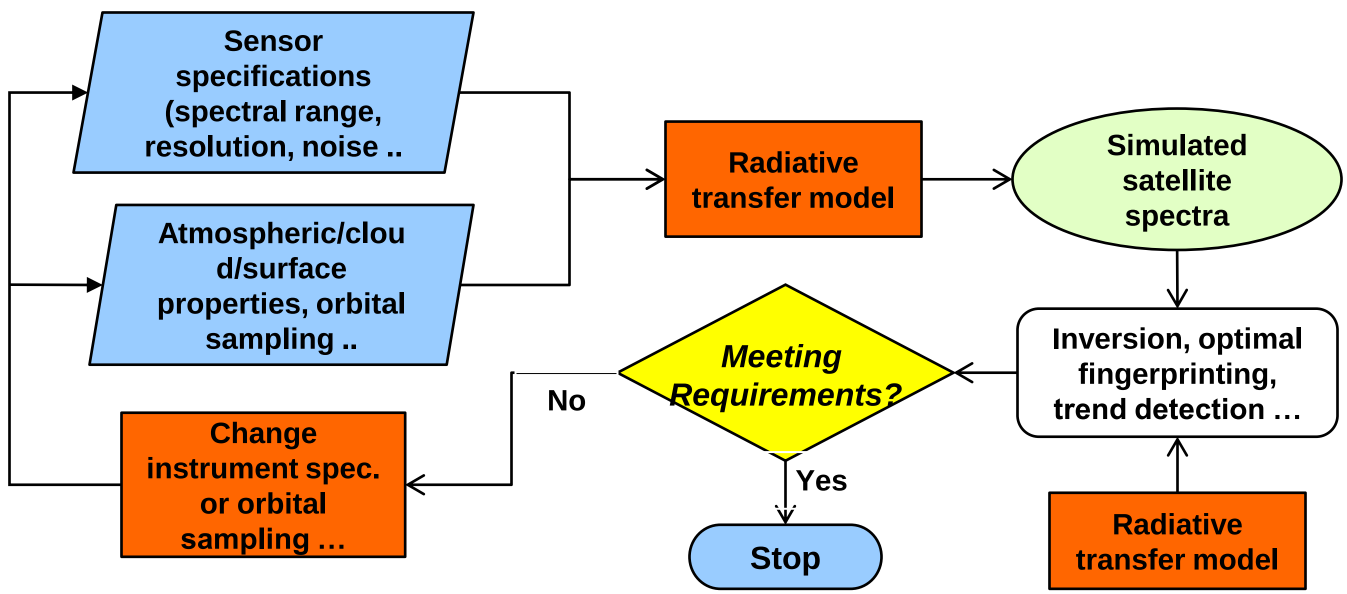
- Advantages of hyperspectral remote sensing data
- Why radiative transfer model is a key component
- How to deal with large amount of hyperspectral data
- Information content analysis
- How to retrieve climate related parameters
- Extending PCRTM to solar spectral region
- Summary and Conclusions

Advantages of Hyperspectral Remote Sensing Data

- One spectrum contains information on numerous climate relevant quantities
  - Vertical atmospheric temperature profiles
  - Vertical atmospheric water profiles
  - O_3, CO_2, CO, CH_4, and N_2O vertical profiles or column densities
  - Cloud height, particle size, optical depth, and phase
  - Aerosol information under heavy loading conditions
  - Land/ocean surface temperatures
  - Land/ocean emissivity spectra
  - Outgoing Longwave Radiation (OLR), TOA radiative flux, cooling rate …
- All parameters are measured simultaneously
  - SI-traceable calibration is done on the whole spectrum
  - No issues with errors associated with multiple data sources
  - Good for radiative forcing/feedback and trend determinations (less error sources)

Why radiative transfer model is important

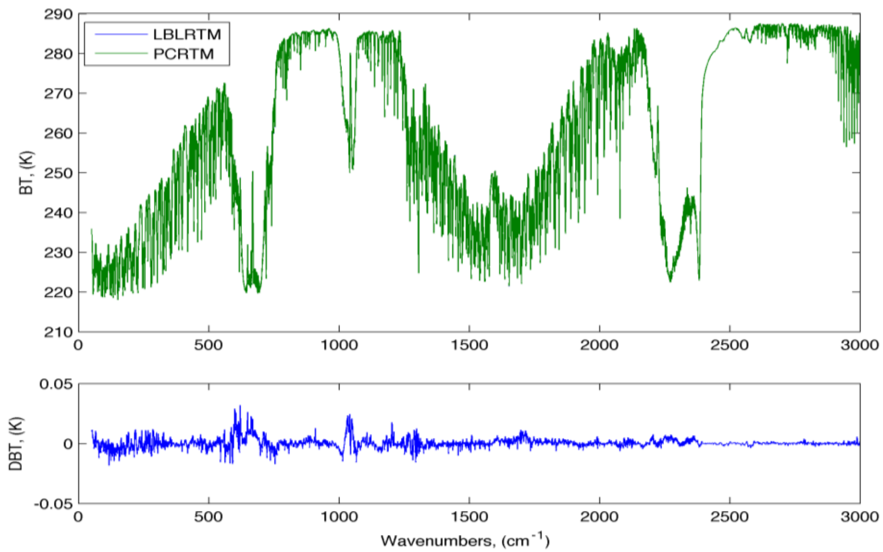
- A radiative transfer model (forward model) is used to quantify the relationship between satellite data (*y*) and atmospheric/surface properties (*x*)
  - $y = F(x, \nu, \theta....)$
- It is needed to separate contributions of climate-related parameters from satellite data
  - Green house gas radiative forcing …
- It is needed to perform end-to-end sensor performance simulations
  - A Key component in climate OSSE
  - Help to refine instrument specifications

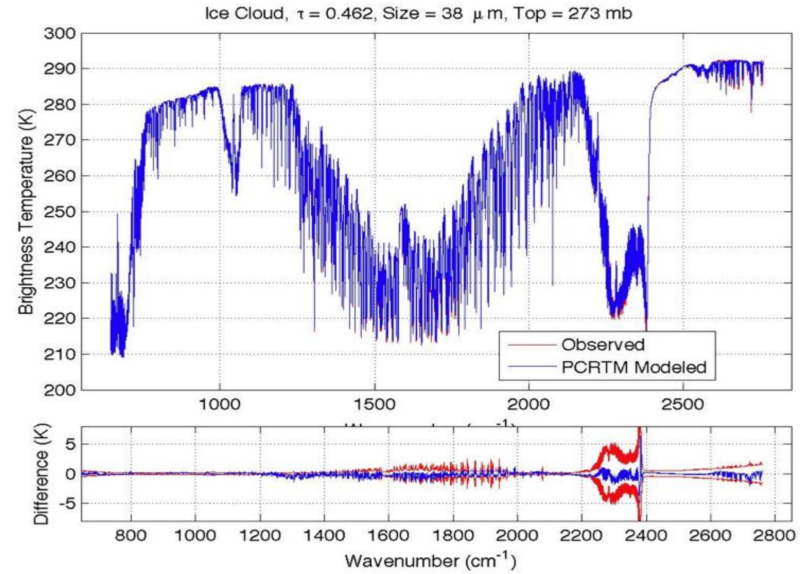


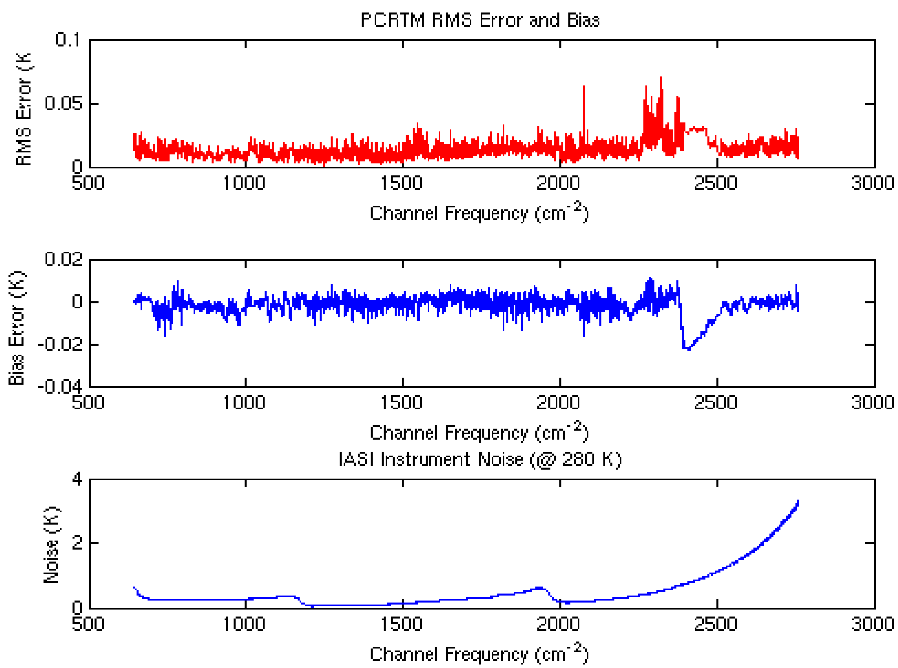
How to deal with large amount of hyperspectral data?

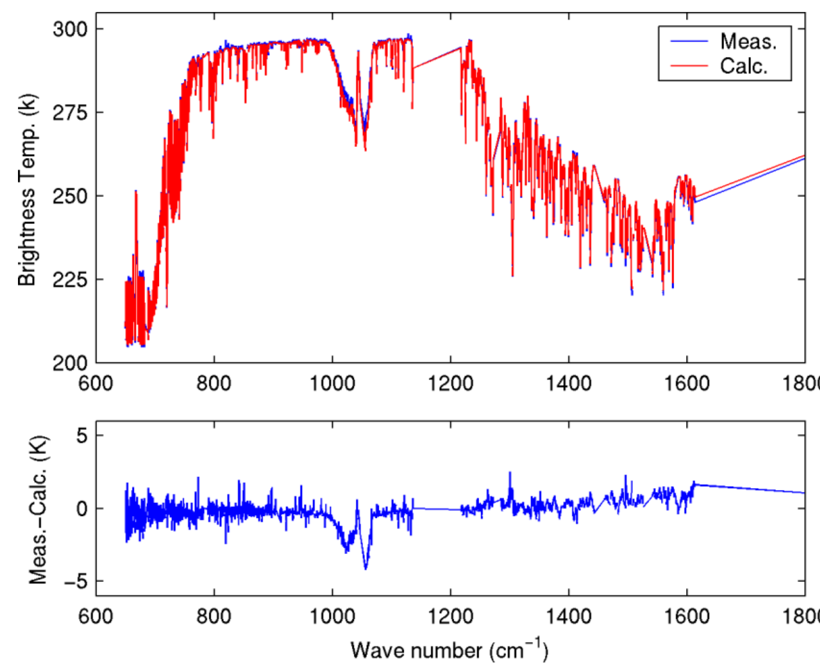
- Radiative transfer equation is a highly non-linear double integral differential equation
  - Need to perform radiative transfer calculations through ~100 atmospheric layers at ~1 million of wavelengths
  - Line-by-line (LBL) forward model is too slow to handle huge amounts of satellite data
- Traditional fast radiative transfer models still too slow to simulate large amount of hyperspectral data
  - Take long time to simulate instantaneous CLARREO spectra
  - Either use super computer or faster models
- Hyperspectral data are spectrally correlated
  - Only the first ~100 leading eigenvectors are used for optimal fingerprinting
  - The ~100 EOF captures all essential information of thousands of channels
- Principal-Component-based Radiative Transfer Model (PCRTM) is ideal
  - Channel-to-channel spectral correlations are captured by eigenvectors
  - Reduce dimensionality of original spectrum by a factor of 10-90
  - Spectral correlations are used to reduce number of radiative transfer calculations
  - Very accurate relative to line-by-line (LBL) RT model
  - 3-4 orders of magnitude faster than LBL RT models
  - A factor of 2-100 times faster than channel-based RT models
- CLARREO PCRTM model have been created with 4 spectral resolutions
  - 0.25 cm^{-1}, 0.5 cm^{-1}, 1.0 cm^{-1}, and 2.0 cm^{-1}
- PCRTM models for AIRS, IASI, and NAST-I have been created
  - Well tested using real satellite and airborne remote sensing data
- References on the PCRTM model and retrieval algorithms
  - Liu et *Applied Optics 2006*
  - Saunders et al., *J. Geophys. Res.,* 2007
  - Liu et al. *Q. J. R. Meterol. Soc. 2007*
  - Liu et al. *ACP 2009*

Typical accuracy of the forward model (< 0.05K relative to LBL)







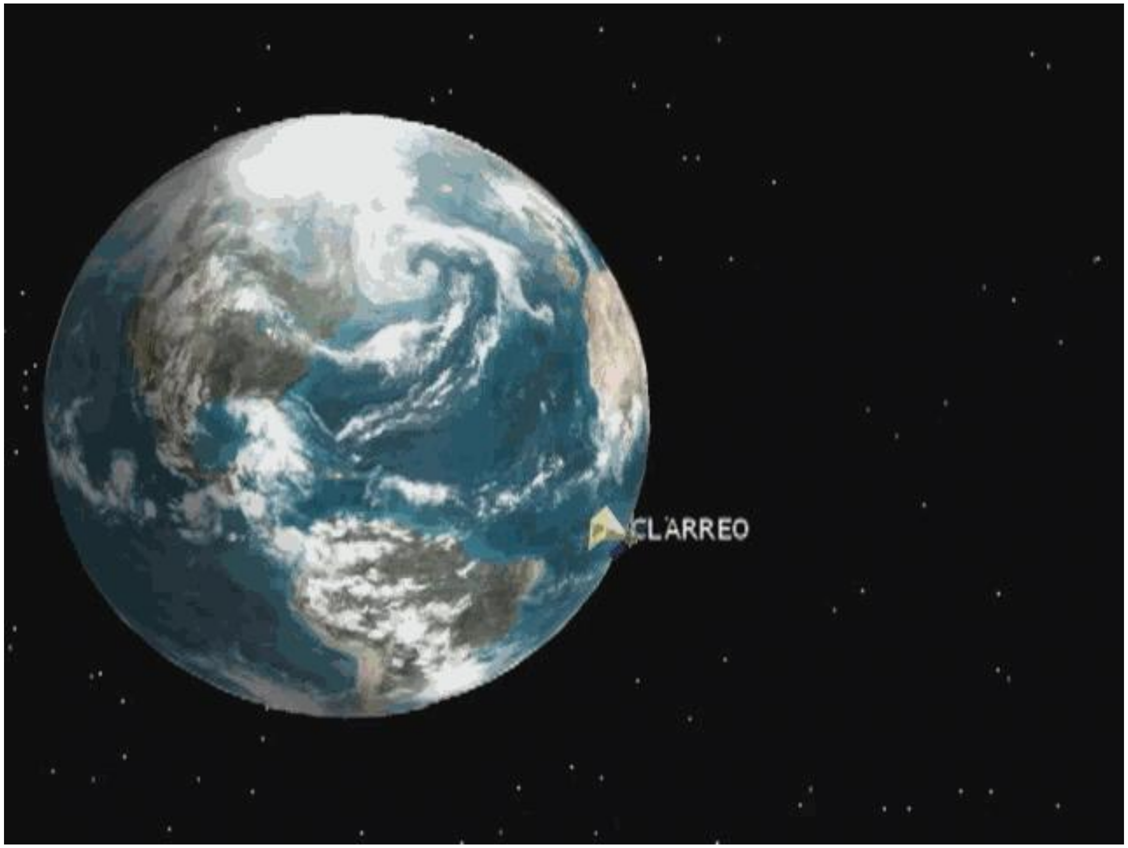


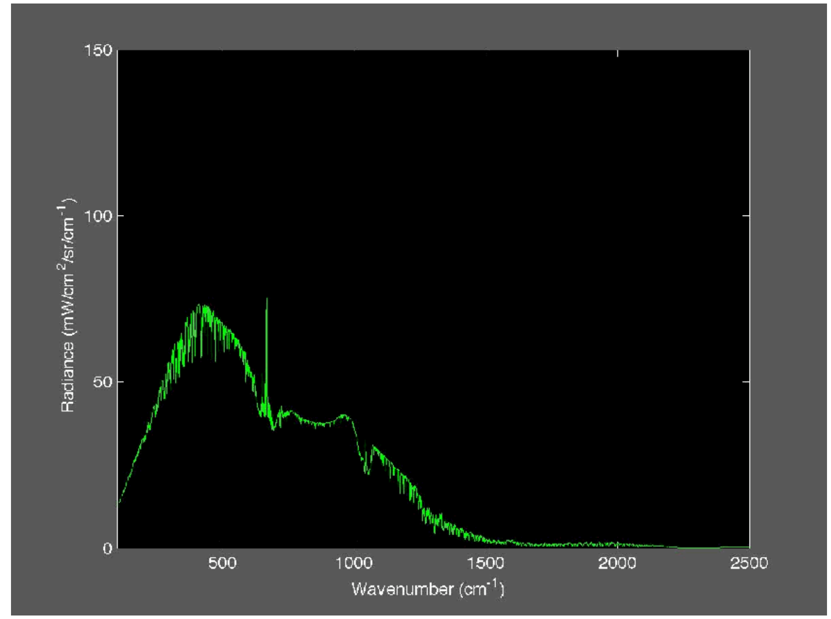
PCRTM is very fast relative to channel-based radiative transfer models and it handles clouds efficiently

- PCRTM needs far less radiative transfer calculations and needs small number of predictors to calculate channel radiances
  - 1-2 orders of magnitude smaller than channel-based RT models
- PCRTM can handle as many as 40 layers of clouds in principal
  - Compares well with DISORT
  - Orders of magnitude faster than DISORT
  - Only slightly slower than clear sky radiative transfer calculation
- PCRTM provides derivatives of radiance with respect to atmospheric parameters for each forward model
  - Saves 10-100 forward model runs compared to finite difference method

NAST-I Spectral Band	Number of Channels	No. of RT Calc. for All NAST Channels	Predictors per Channel
PCRTM	8632	310-900	0.04-0.1
PFAST	8632	8632	~40
OSS	8632	22316	2.59

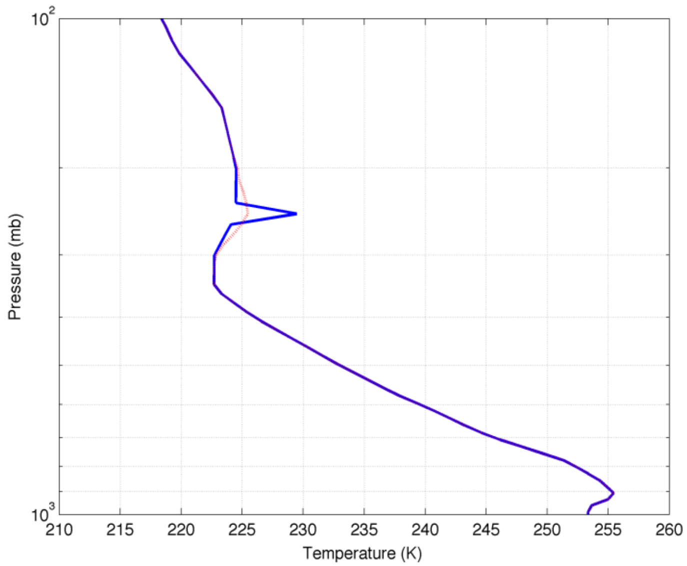
Examples of simulated CLARREO spectra and orbital observations using PCRTM

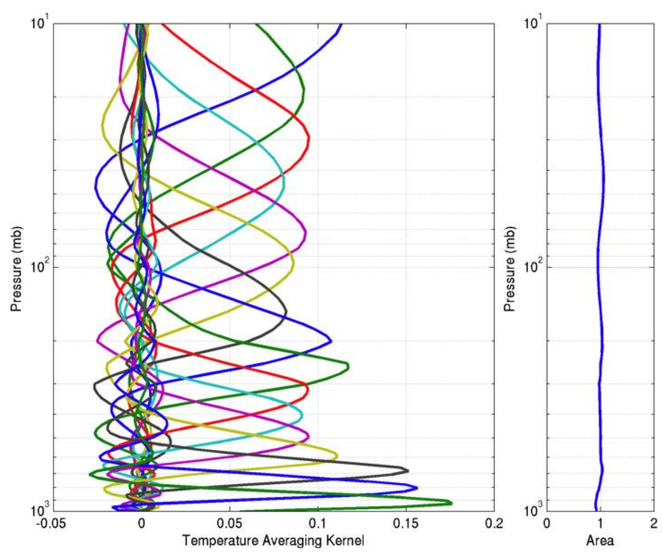




- Movie made by Joe based on Dave’s Young’s original discussion
- Spectra simulations based on Seiji and Fred’s work
    - CERES single FOV product, MODIS cloud field, and GOES-4 profiles
    - Using about 100 CPUs
    - Takes PCRTM 14 days to simulate 6 years of hyperspectral data
    - Takes MODTRAN (a channel-based radiative transfer model) 85 time longer

CLARREO Information Content Analysis
(methodology)





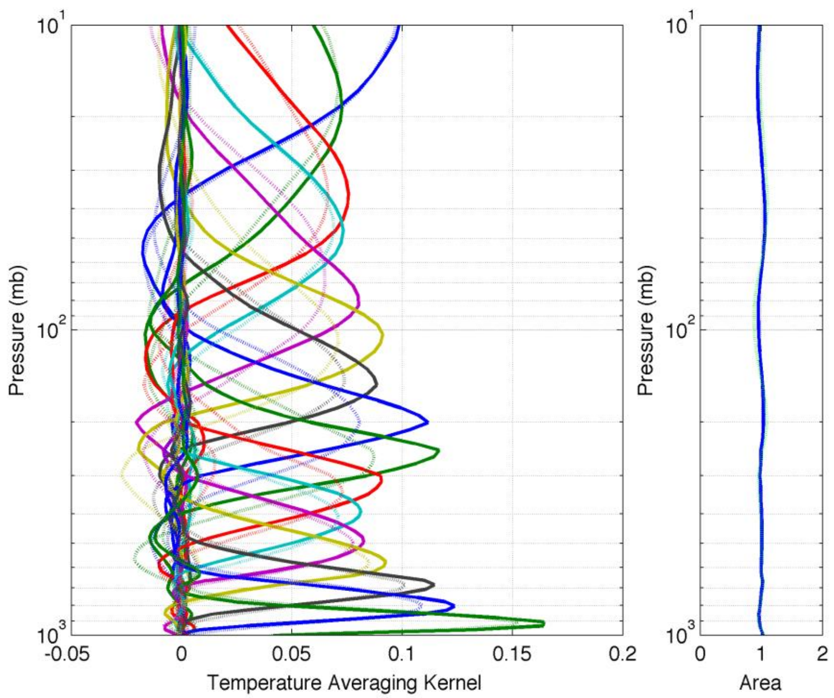
$$A_x = \frac{\partial x_n}{\partial x} = (K^T S_y^{-1} K + S_a^{-1})^{-1} K^T S_y^{-1} K$$

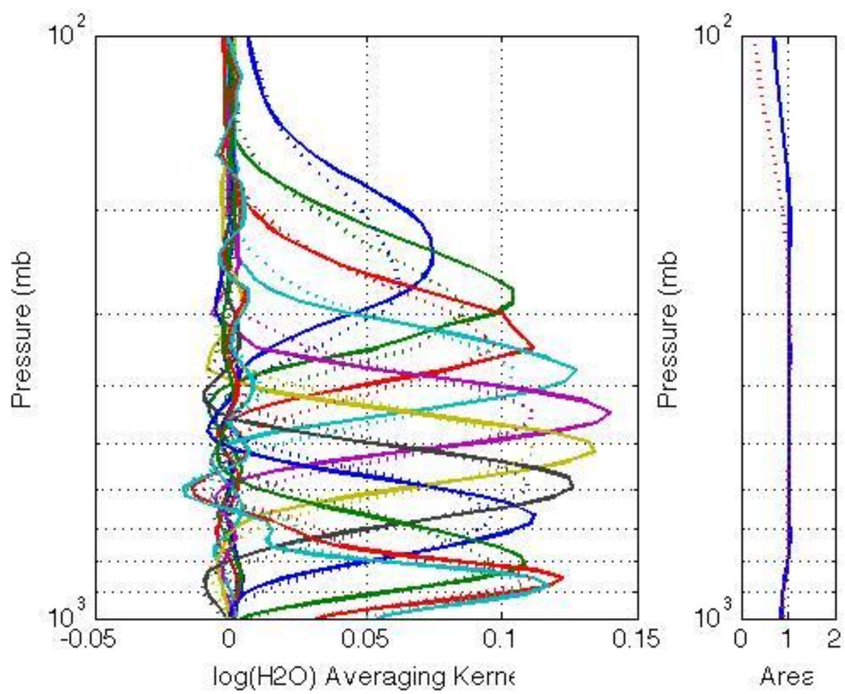
$$H_x = -\frac{1}{2}\sum_i \ln\left|I - A_x\right| , \quad d_x = tr(A_x)$$

- Averaging kernel provide information on retrieval system
  - Location and magnitude of the peaks relate to information at a particular height
  - Width of the peaks relate to vertical resolution
  - Integrated area of the averaging kernel provides relative contribution from a priori and measurements
  - Trace of A_x provides degree of freedom
- Averaging kernel is profile dependent
  - Generate CLARREO spectra with hundreds of atmospheric profiles
  - Probability Density Function (PDF) or mean of the A_xFor different instrument configurations (*K*)
    - Different noise (S_y)
    - Different spectral resolution (*K*)
    - Different band coverage (*K*)
    - With and without Far IR band (*K*)

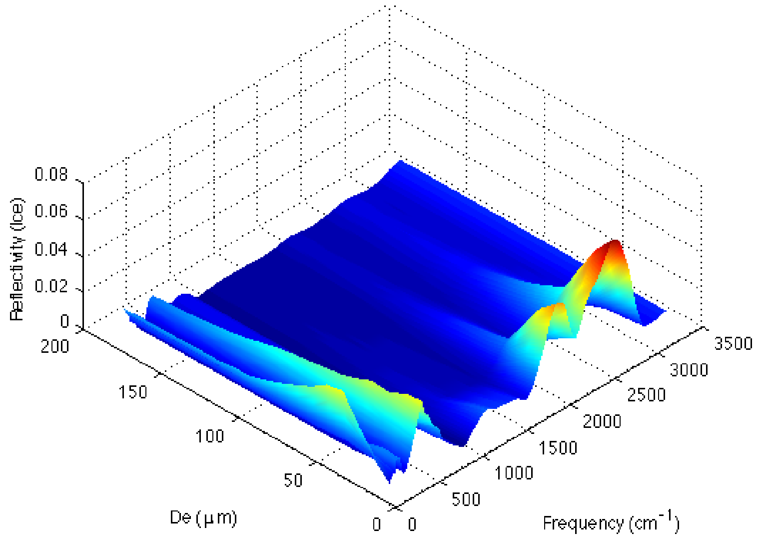
CLRREO Information Content Analysis
(Impact of Far IR band)

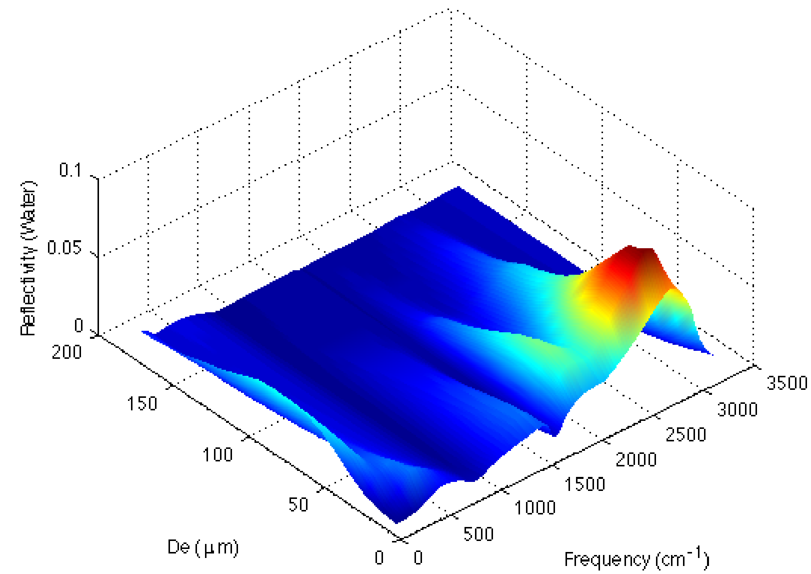
- The baseline spectral resolution for this study is 1.0 cm^{-1}
  - Need more realistic CLARREO instrument noise
- Far-IR impact on atmospheric vertical temperature information
  - The vertical resolution decreases without far-IR portion of the spectrum (dotted lines, DOF: 8.11 vs. 9.34)
- Far-IR impact on atmospheric vertical water information
  - The vertical resolution decreases without far-IR portion of the spectrum (dotted lines, DOF: 4.48 vs 6.13)
  - The far-IR band provide more information for higher altitude moisture
- There are other things to consider for Far-IR
  - Far-IR spectral region is essential in TOA long-wave radiance flux calculation
  - Far-IR provides more constraints on atmospheric clouds

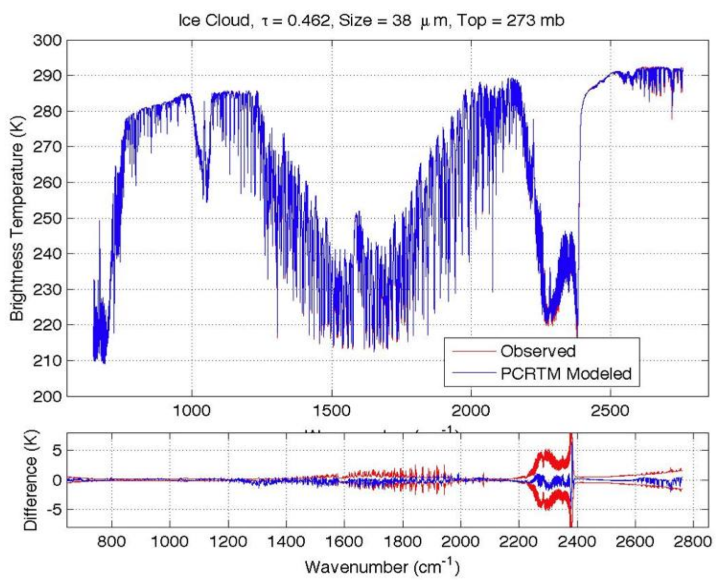


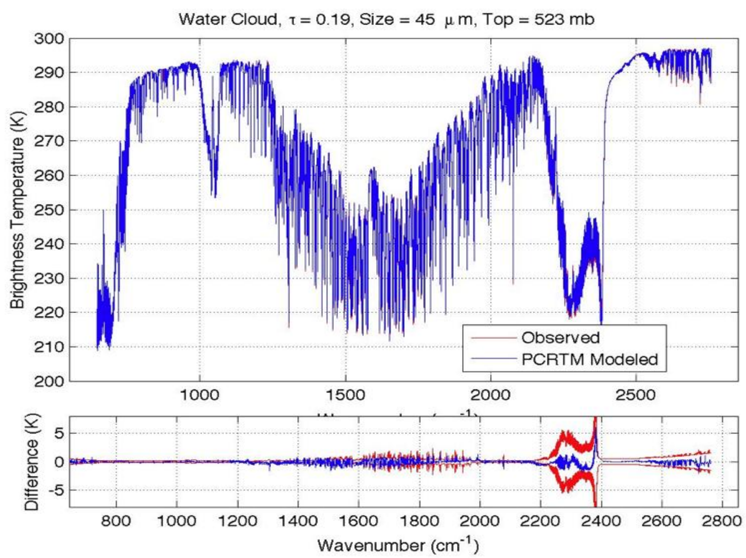


Hyperspectral data is capable of separating Ice clouds from water clouds









Ways to explore information content of CLARREO hyperspectral data

- Invert each instantaneous spectrum first
  - Obtain atmospheric, cloud, and surface properties
  - Study zonal/global mean of the product
  - Perform time series analysis (taking into account of natural variabilities)

$$X_{n+1} - X_a = (K^T S_y^{-1} K + \lambda I + S_a^{-1})^{-1} K^T S_y^{-1} [(y_n - Y_m) + K(X_n - X_a)]$$

- Perform radiance averaging first
  - Perform retrieval of individual climate variables using spectral fingerprinting method
  - Less sensitive to instantaneous instrument noise

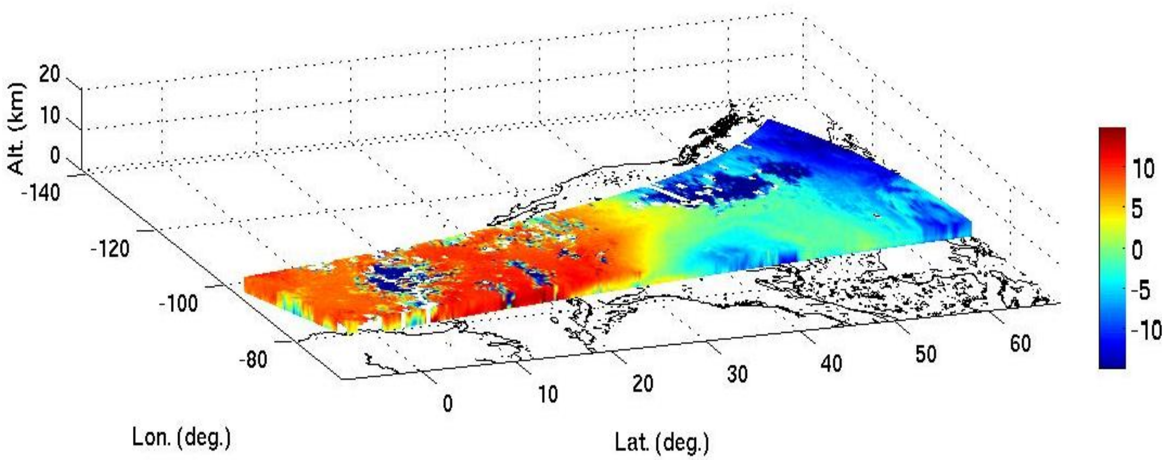
$$y = Sa + r$$

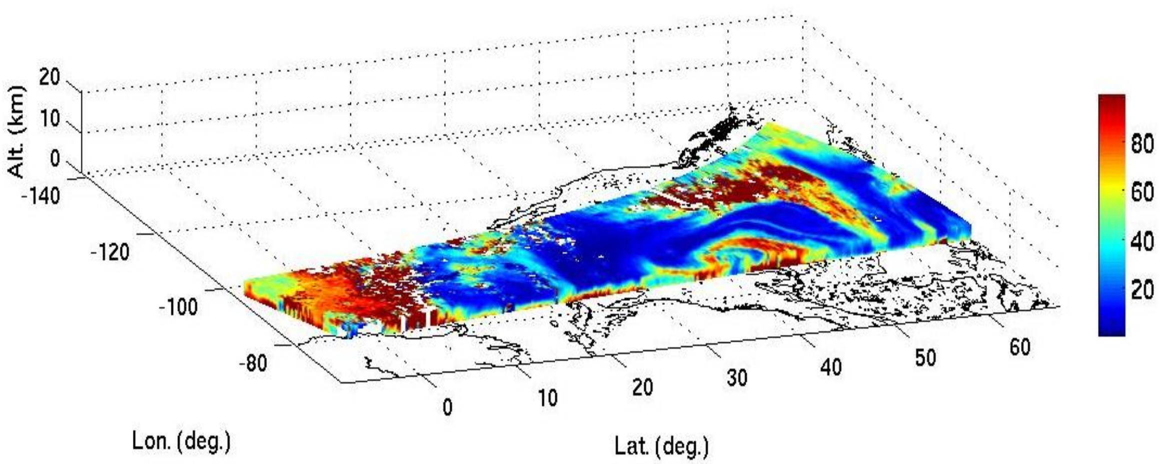
$$a = (S^T \Sigma^{-1} S)^{-1} S^T \Sigma^{-1} y$$

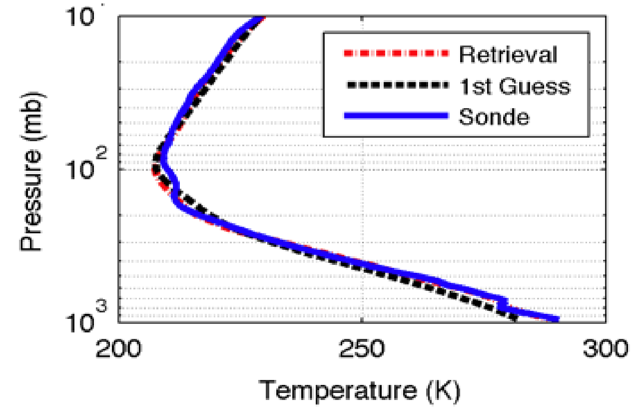
$$\Sigma = \Sigma_{nat} + \Sigma_{shape} + \Sigma_{nl}$$

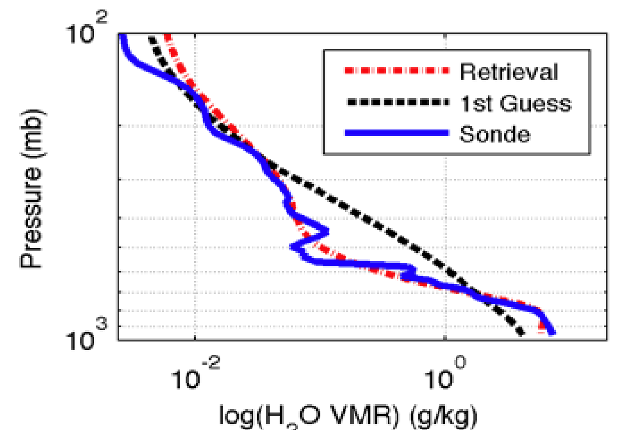
A method has been developed to retrieve cloud and atmospheric properties simultaneously

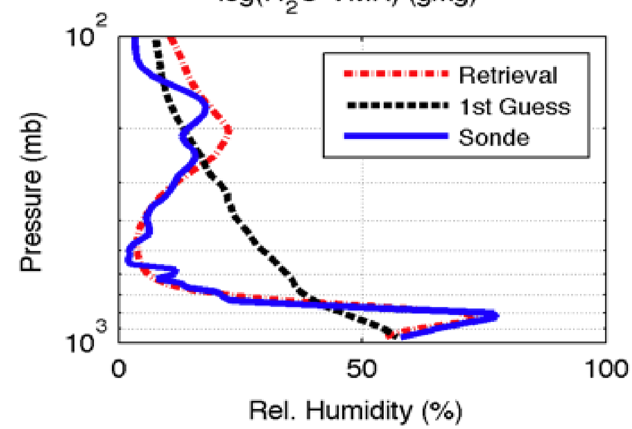
- Temperature, moisture, and ozone cross-sections
- Plots are deviation from the mean
- Fine water vapor structures captured by the retrieval system
- A very cloudy sky condition





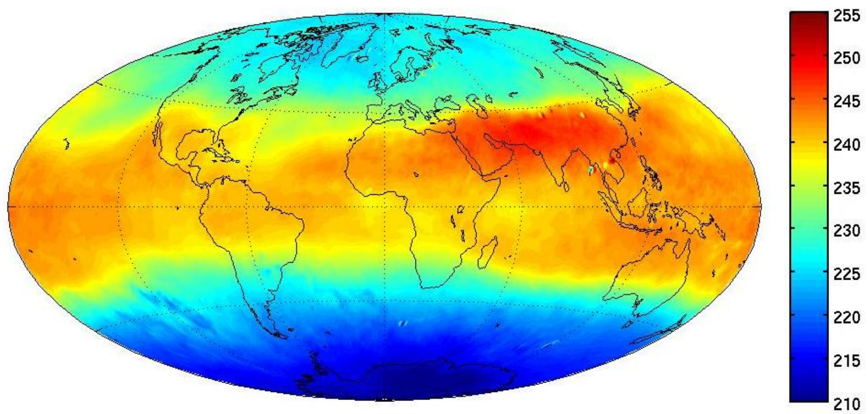




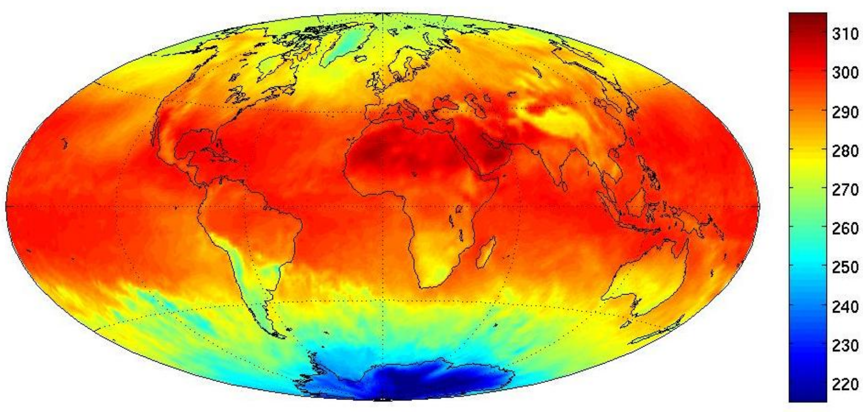


Example of retrieved global atmospheric and surface properties using PCRTM algorithm

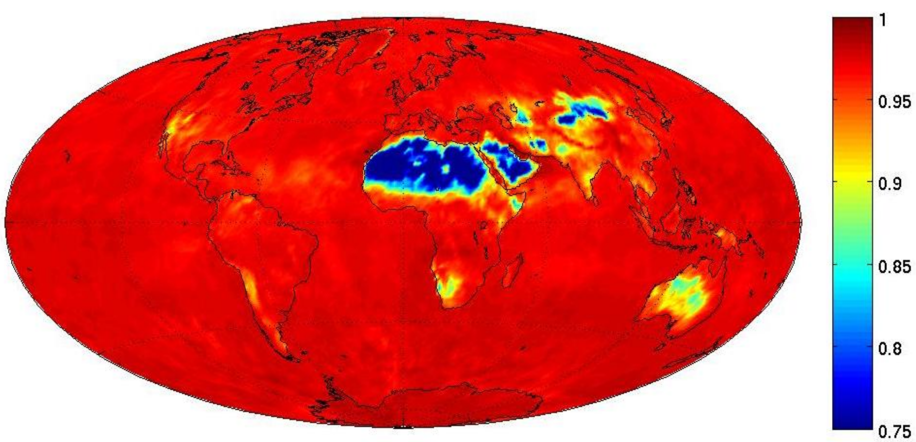
Atmospheric temperature at 9 km for July 2009



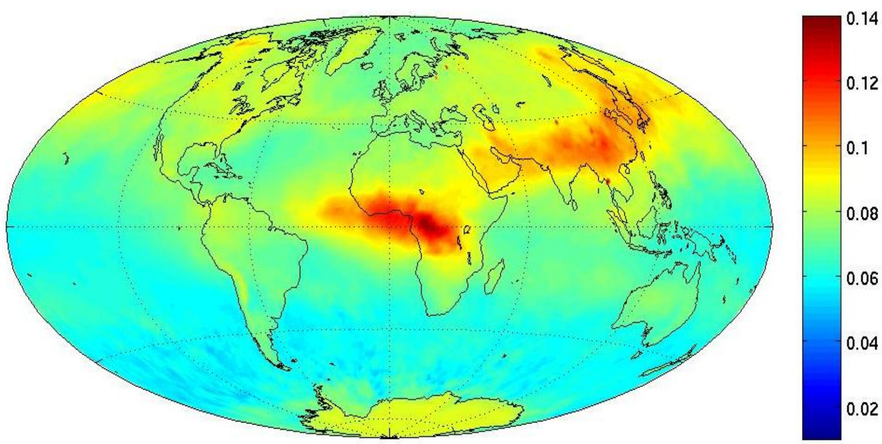
Surface skin temperature for July 2009



Surface emissivity for July 2009

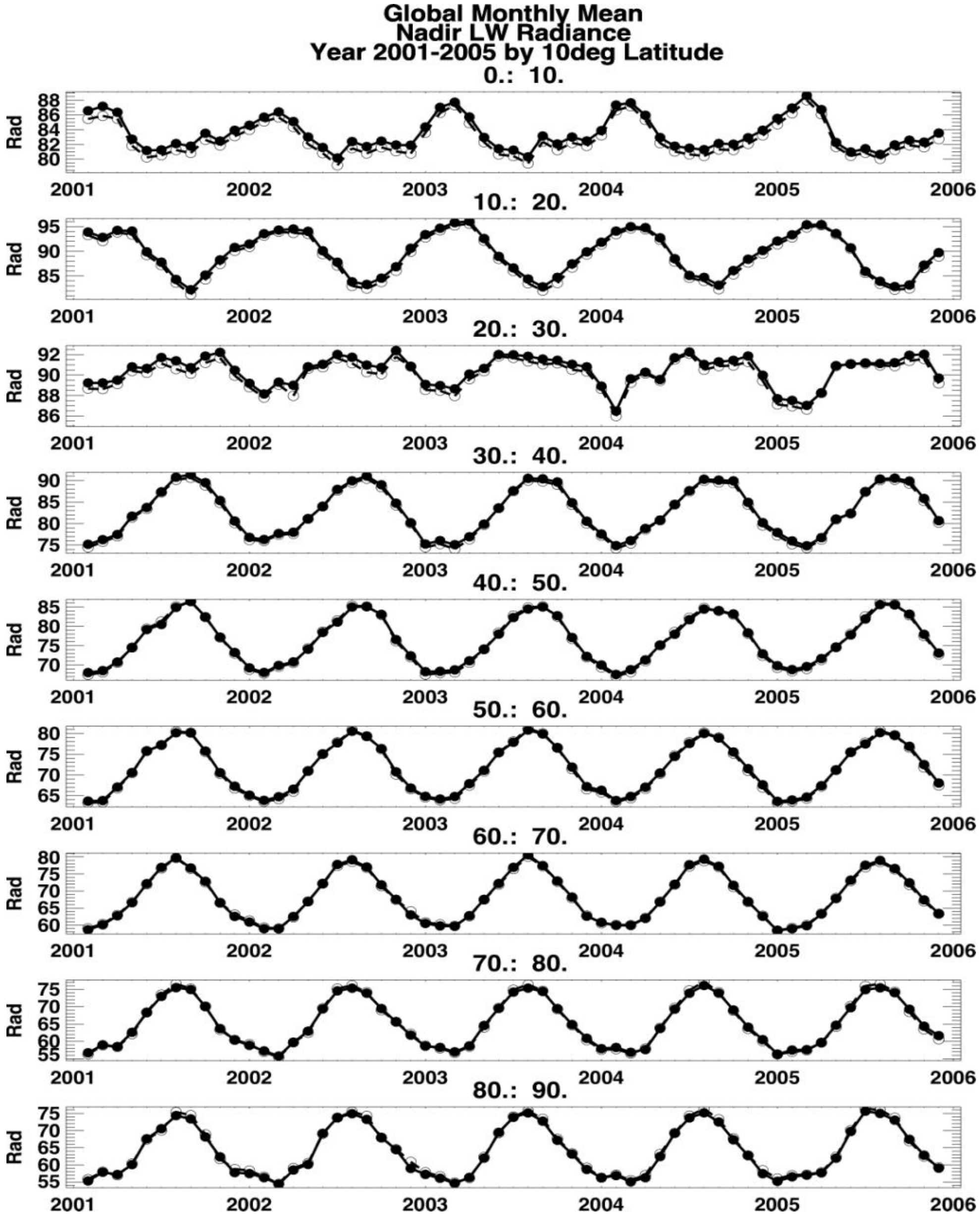


Atmospheric carbon monoxide mixing ratio for July 2009

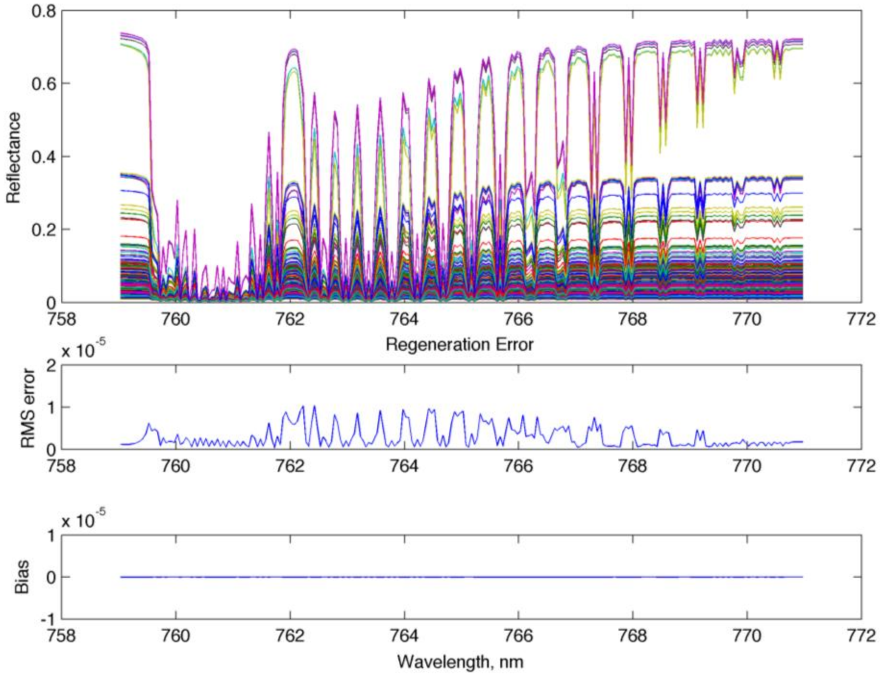


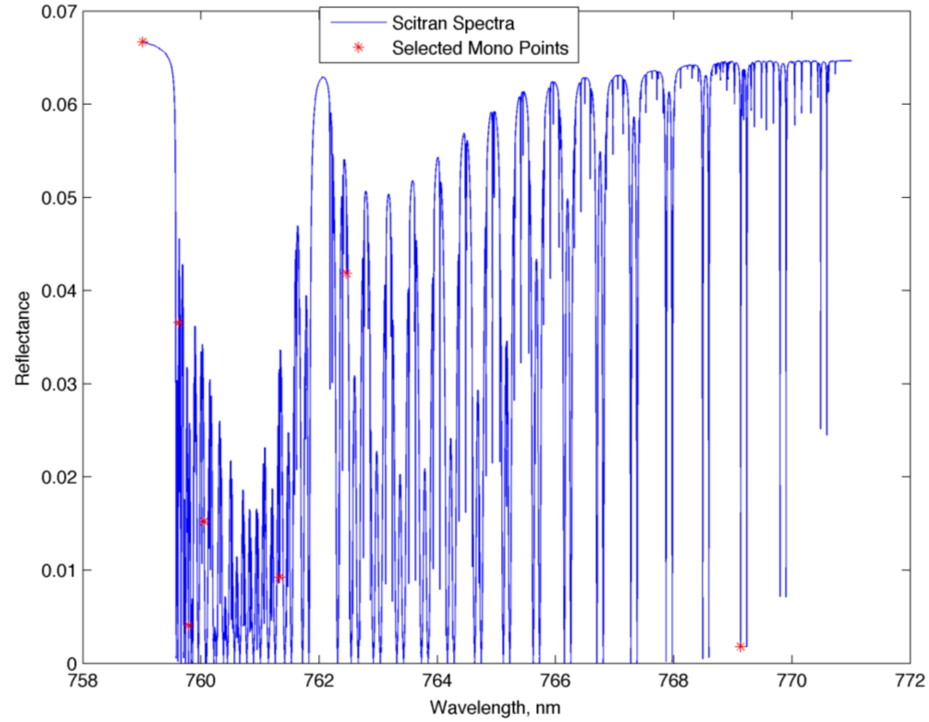
Comparison of PCRTM calculated LW radiances with CERES observations (work done by Fred and Seiji)

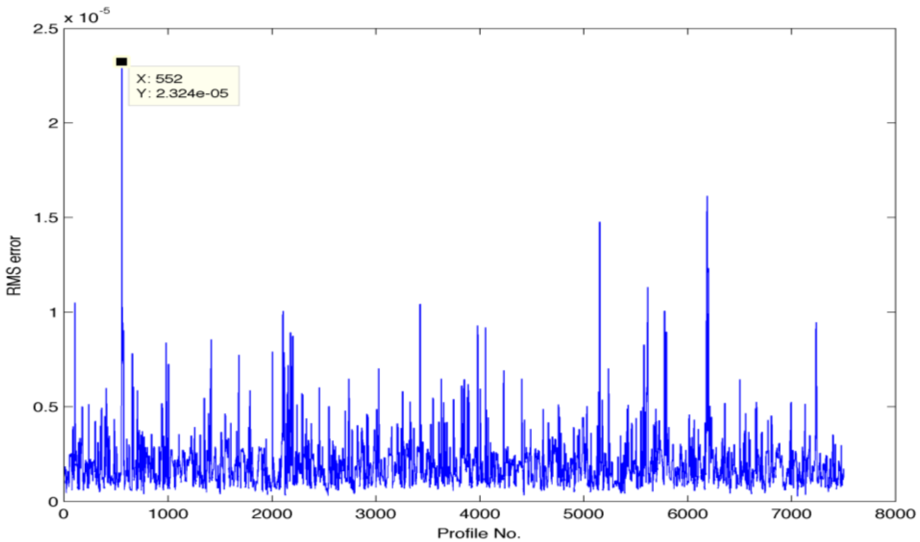
- This dataset has realistic cloud derived from MODIS observations
- Compares well with CERES
- Will use this dataset to compare the performance of direct retrieval vs. spectral fingerprinting



Apply PCRTM to Orbiting Carbon Observatory (OCO) O_2 A-band

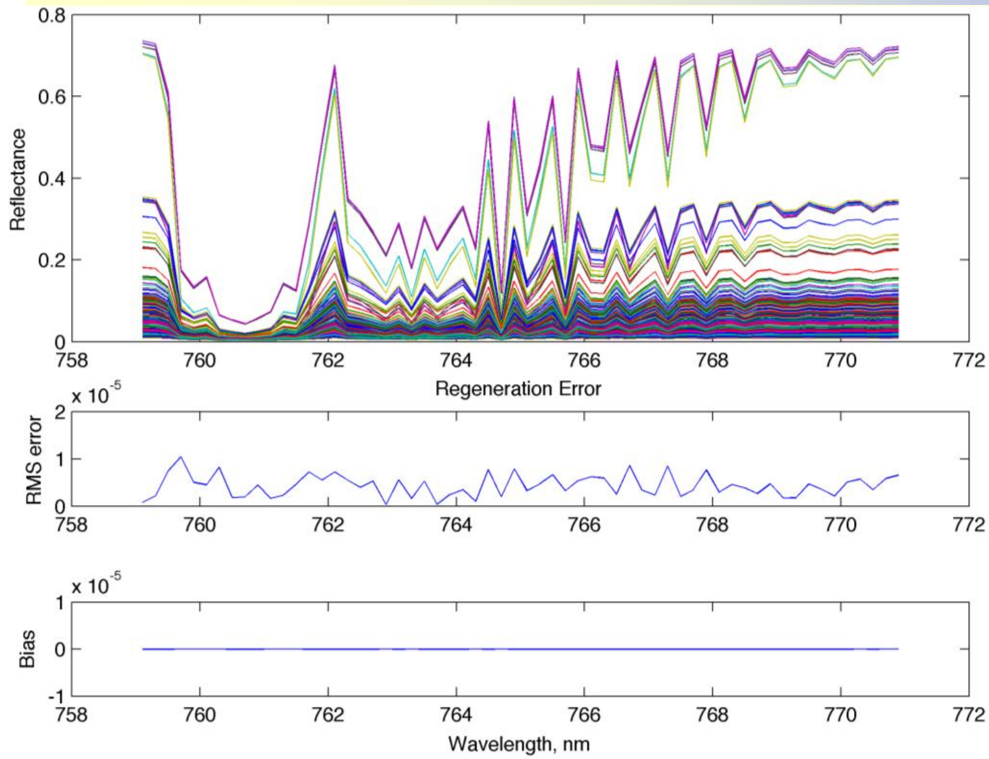


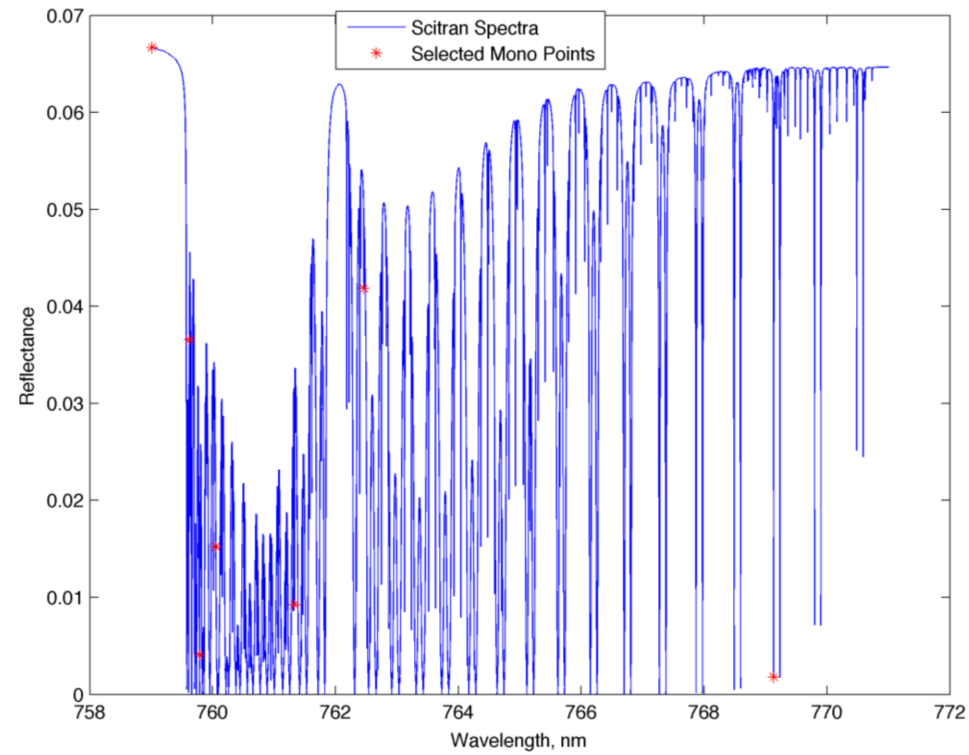




- Model reflectance of R-branch of O_2 A-band
- OCO spectral resolution (0.045 nm)
- 6 EOF, 7 Mono needed for R-branch of O_2 A-band
- Maximum RMS error < 2.32×10^{-5} for 7500 sample
    - Various clouds
    - Aerosols
    - Ocean and various land surface types
    - Various atmospheric profiles
- Bias error close to zero

Apply PCRTM to SCIAMACHY O_2 A-band





- Model reflectance of R-branch of O_2 A-band
- SCIAMACHY spectral resolution (~0.2 nm)
- 5 EOF, 7 Mono needed for R-branch of O_2 A-band
- RMS error < 3×10^{-5}
- Bias error close to zeros
- Will extend the method to CLARREO spectral resolution (~4 nm spacing)
  - Need even less point
  - Will enable much faster OSSE and end-to-end simulations

Summary and Conclusions

- Forward model is a key component in analysing hyperspectral data
  - End-to-end sensor trade studies
  - Realistic global long term data simulations and OSSE experiment
  - Satellite data analysis and data assimilations
- PCRTM is a useful tool specific for hyperspectral data with thousands of channels
  - PCRTM compresses thousands of spectral channels into 100-200 EOFs
  - 3-4 orders of magnitude faster than Line-by-line models
  - 2-100 times faster than traditional forward model
  - Very accurate relative LBL models
  - Multiple scattering cloud calculations included
  - Model has been developed for AIRS, NAST,IASI, CLARREO
  - Work started to extend the method to UV-VIS spectral region (OCO, SCIAMACHY)
- Study underway to compare direct retrieval vs spectral fingerprinting to derive climate related quantities
  - Using IASI as proxy data
  - Using simulated spectral from satellite and model products